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GALACTIC DARK MATTER AND TERRESTRIAL PERIODICITIES

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SUMMARY. Analysis of recent geological databases reveals the presence of a ~26.5 Myr periodicity in the terrestrial record of the last ~200 Myr. The same periodicity is found to be present, at a high confidence level, in the record of impact cratering on Earth. It thus appears that global disturbances are modulated or caused largely by exogenous forcing. The likely source is a periodic comet influx caused by Oort cloud disturbance as the Sun oscillates vertically through the Galactic disc. The Earth may thus be regarded as a probe of the disc environment; and to account for the periodicity, the Galactic disc is required to have a substantial dark matter component ($\sim 0.15 M_{\odot} pc^{-3}$). The purpose of this paper is to review the relevant observational framework, and to describe the basic astro- and geo-physical processes which now seem to underpin evolution on Earth. Attention is drawn in particular to recent oceanic sediment evidence which seems to confirm a continuous sequence of events from periodic Galactic forcing through the influx of giant comets (diameter $\gtrsim$ 100 km) into stable sub-Jovian orbits at the rate of ~10 Myr^{-1} and the

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resulting climatic disturbances due to their disintegration in near-Earth space. This rate, producing episodic multiple threats to the Earth by bodies in the sub-kilometre range, is numerically comparable to the long-term cratering flux to Earth due to 'one-off' $\gtrsim 1$ km asteroids and comets. The resulting *current* hazard to Earth, amounting to a more substantial input and explosion megatonnage *in toto,* is both more complex and more profound.

1 Geological beginnings

Catastrophes due to celestial inputs have long been a source of anxiety to mankind. Both impacts and airbursts may be envisaged, each with a variety of associated physical effects *e.g.* explosive, seismic, diluvian, atmospheric dusting *etc.* During the late 20th century, however, terrestrial catastrophism studies have been largely a Space Age spin-off, following the discovery that impact cratering is a widespread Solar System phenomenon. It has generally been perceived as having rather few short-term implications for mankind, say, on millennial and centennial timescales. During the early 19th century on the other hand, terrestrial catastrophism studies were occurring in the wake of earlier meteor/meteoritic 'bombardment' events and these were a source of a good deal more concern (*e.g.* Clube 1995). Thus the closing decades of the 18th century were a period of intense intellectual ferment and revolutionary zeal such as had previously afflicted European and American society during the central decades of the 17th century (*e.g.* Ball 1975, Thomas 1971, Goldstone 1991); these periods also correspond to the last major outbursts of doomsday prediction and their customary millennialist response. But what is remarkable about the later outburst in particular is its characterization near the turn of the century by secular modes of thought (*e.g.* Bloch 1985) which meant that millennialism was essentially replaced by utopianism and doomsday prediction came to be regarded as a mindless extravagance. Thus did mankind settle on a uniformitarian perception of its future celestial environment just as supernaturalism could no longer be entertained as an explanation of the terrestrial record. The uniformitarianism-catastrophism issue came of course to be widely debated at this time during geology's emergence as an independent science. That uniformitarianism was to remain in place owed much to the state of public opinion; the scientific debate was only reconciled however towards the end of the 19th century when the sequence of major events in Earth history was eventually recognised as episodic (*e.g.* Hallam 1989).

By excluding 'catastrophism' and developing its episodic theme, it seems that geology then became the fulcrum around which the sciences subsequently diverged. For while the biological and social sciences now steered an unashamedly uniformi-

tarian course, essentially avoiding confrontation with public opinion, the physical sciences (especially geophysics) adopted a lower profile and, though cultivating a generally mechanistic view of episodic phenomena, did not exclude a catastrophist interpretation of events. Thus we find the proposal early this century that the ebb and flow of major events in Earth history was fundamentally periodic and in possible synchronism with the Solar System's vertical crossings of the Galactic plane (Holmes 1927). The absence of a straightforward physical explanation of the evident correlation, not to mention the cultural hurdles, meant the facts were treated with suspicion. Nevertheless, our knowledge of the Solar System's vertical oscillatory motion within the Galactic disc, including its period, began to be placed on a secure footing soon afterwards (Oort 1932) and it has eventually come to be accepted that a common periodicity of $\sim$26 Myr could be ascribed to such as the cratering record, the mass extinctions of life, sea-level variations, mountain-building episodes and the frequency of geomagnetic reversals (Seyfert & Sirkin 1979, Raup & Sepkoski 1984, Mazaud *et al.* 1984, Rampino & Caldeira 1992).

Looking back now, it is perhaps strange that such a prominent Galactic signature in the terrestrial record was seen more for its curiosity value than for its physical significance (McCrea 1981). However, there was no lack of ideas and the problem, it is clear, was to find a physical model in accordance with data which actually worked! Encounters with interstellar clouds, for example, or the explosion of nearby supernovae were both too rare and spasmodic for a period as short as $\sim$26 Myr. Furthermore, it did not appear particularly plausible to suppose that these and other phenomena of the Galactic environment could seriously influence processes occurring deep within the mantle and core of the Earth. This however is where the problem lay for the reluctance of many Earth scientists during the early twentieth century to relinquish 'terra firma' is by now legendary. Thus, not even the evidence of continental drift and sea-floor spreading were immediately persuasive so far as the massive circulations within the core and mantle were concerned. However, by the 1960's, the question how these circulations could be intermittently disturbed was no longer seriously discounted.

One idea was to attribute episodes of tectonic activity solely to the build-up of instabilities in the underlying circulation *e.g.* through continuous cooling of the Earth and the freezing out of its metallic core. Another was episodic dust-loading and increased optical depth of the atmosphere in parallel with the reduced heat loss by convection from the interior of the Earth. The obvious corollary of the latter was global climate as an instrument of the episodic redistribution of angular momentum between polar ice and equatorial ocean: this then induces sub-crustal movements across the mobile plates at the surface of the Earth and produces the

necessary changes in the underlying circulation to account for the reduced heat loss by convection. A significant aspect of the plate-tectonic revolution therefore was its Space Age setting and the rapidly growing evidence (a surprise to astronomers) for minor Solar System bodies commonly encountering the planets and their satellites. It was but a short step to tectonic episodes brought on by dust-loadings due to the ebb and flow of comets and a Galaxy which might have something to do with the presence of cometary impactors in near-Earth space (Napier & Clube 1979, Clube & Napier 1984).

2 Cometary perspectives

The celestial inputs to Earth comprise a wide range of sizes and material strengths represented at the top end of the range by the observed comets and asteroids. Bodies large enough or robust enough to form impact craters at ground level are however but a small fraction of the total mass input. Thus the mass input as a whole generally comprises the smaller and more fragile bodies (meteoroids) which contribute to the airbursts and disintegrations currently observed at low and high levels above ground zero respectively. Of these, the high level disintegrations are perhaps less well known but their mass input tends to match that of the preformed (zodiacal) dust from space (Fechtig 1982). Zodiacal dust particles are however apparently predominant amongst the detected particles at lower levels indicating that much of the higher level disintegrations undergoes further comminution (to the submicron size) during its (more extended) atmospheric descent. The submicron dust component probably represents by far the greatest mass input at ground level where it is incorporated in sedimentary layers. Impact craters and sedimentary interplanetary dust particles may therefore betoken the arrival from space of a still largely unmonitored population of inner Solar System bodies which (Section 5) is also the probable primary cause of climatic change and deep-seated terrestrial phenomena.

The comet flux in near-Earth space is the likely main source of the fragile material considered here and there were several significant new insights regarding this flux during the 1960s and 1970s. First there was the suggestion that part of the Earth-crossing asteroid/meteoroid population might be derived from degassed short-period (SP) comets deflected into sub-Jovian space (Opik 1963). Secondly there was the suggestion that a substantial component of the zodiacal dust complex might be evolved from meteoroids (and asteroids) deriving from a massive comet deflected into sub-Jovian space which is also the progenitor of Comet P/Encke (Whipple 1967). Following the earlier insight that long-period (LP) comets are

deflected into SP comets through sequences of planetary perturbations (van Woerkom 1948), leading to the realization that comets, as they split and fragment, become increasingly faded and resilient (Oort 1950), it became increasingly probable that part of the Earth-crossing asteroid and zodiacal dust systems near the ecliptic plane in sub-Jovian space underwent substantial, intermittent replenishment through the arrival of successive, massive comets in low-inclination orbits from the Oort cloud (*cf* Everhart 1972). With the further realization that impacts of great energy, capable of yielding geological signatures such as mass extinctions (Urey 1973), were both commonplace and statistically uniformitarian on geological timescales (Hartmann 1978), it was natural to suppose that Oort cloud perturbations arising from the Galactic environment would give rise to both periodic and stochastic episodes of terrestrial bombardment through surges in the flux of (giant) cometary debris in sub-Jovian space (Clube & Napier 1984, 1986). The novel and attractive feature of this proposition, finally challenging the long-standing thesis that terrestrial periodicities should be seen purely for their curiosity value, was of course the fact that long-term as well as currently active processes, on the Earth and in interplanetary space, came within the scope of a unifying astronomical theory. Such a theory, like the knowledge of impact cratering itself, did however have disturbing cultural implications as well – thus it could even be said that the effective re-instatement of a predictable celestial interference in terrestrial affairs constituted a revival of the basic astrological principle! It appeared nonetheless that the putative galacto-terrestrial relationship was now capable of being validated in a methodologically sound manner through direct observational and theoretical assessments of the astronomical and terrestrial environments.

By the 1980s, the fact of a specific galacto-terrestrial mechanism mediated by comets had focussed attention on (a) the process whereby captured (giant) cometary inputs were deflected into sub-Jovian space on timescales $\lesssim 1$ Myr (*e.g.* Bailey *et al.* 1994); (b) the process whereby (giant) cometary debris affected the Earth on timescales $\lesssim$ 0.01 Myr (*e.g.* Steel *et al.* 1994), and (c) the process whereby (Galactic) perturbations of the Oort cloud are associated with the $\sim$26 Myr modulation impressed upon the terrestrial record. Turning to the latter issue in the present paper, the first step towards a new understanding came with the realization more or less simultaneously that the standard Oort cloud (with semi-major axes $\gtrsim$ 20,000 AU) was liable to be inflated and even dispersed in the presence of typical molecular cloud encounters (Clube & Napier 1982, 1986; Napier & Staniucha 1982) and liable to be replenished in the presence of a dense inner core to the cometary cloud (*i.e.* comets with semi-major axes $\sim$10,000 AU). The possible existence of a dense inner core of comets (Oort *loc. cit.*) had essentially been overlooked (Hills 1981), albeit some comets from the region of the core were

already observed (Fernandez & Ip 1987, Heisler *et al.*1987, Heisler 1990) and attributed to a recent cometary shower (Yabushita 1979, 1989). On the other hand, taking note of the fact that the standard Oort cloud usually marks the closest region to the Sun of perturbations by typical stars and Galactic tides (*e.g.* Fernandez 1992), it was also conceivable that a more persistent perturbation of the proposed inner core by more frequent low-mass objects (*cf* Oort, *loc. cit.*) had recently replenished the standard Oort cloud as well as enhanced the number of Jupiter family capturees (Bailey 1992), albeit the latter may be multiplied further as a result of tidal splitting during Jovian capture (*cf* Clube & Napier 1986, Rickman 1990) à la Shoemaker-Levy. The significance of these findings lies in the number of effective low-mass perturbers penetrating the inner Oort cloud which may vary significantly during the course of the vertical solar orbit (Section 4) while the strength of the continuous Galactic tidal force across the Oort cloud may likewise reflect systematic variation in the 'slab density' which lies between individual comets and the Sun (Section 3; *cf* Matese *et al.* 1995). Both processes introduce a cyclic variation in the near-parabolic cometary flux and are thus a potential source of periodicity in the terrestrial response.

The amplitude, periodicity and phase of the terrestrial cycle represent crucial (well determined) data against which the details of the cometary hypothesis may now be compared. In this paper, we examine a number of geological databases and confirm the existence of strong periodic surges in the terrestrial record (*cf* Section 6). The comet flux is apparently controlled by *two* basic out-of-phase ~26 Myr cycles of differing amplitudes, whilst also revealing longer period variations (~100–200 Myr) which may be related to the passage of spiral arms. The strength and periodicity of the combined oscillation requires the existence of a substantial density of dark matter in the Galactic plane, *viz.* $\sim 0.15 M_{\odot} pc^{-3}$, and is consistent with the existence of Machos of mass $\sim 0.03 M_{\odot}$ (*cf* Gerhard & Silk 1995).

3 Tidal perturbations of the Oort cloud

We consider first the perturbation effects of the continuous Galactic tide. It turns out (Antonov & Latyshev 1972; Byl 1983, 1986; Smoluchowski & Torbett 1984; Torbett 1986; Heisler & Tremaine 1986; Morris & Muller 1986; Matese *et al.* 1995) that the characteristic change in the transverse velocity of a LP Oort cloud comet due to the action of the vertical tide over an orbital period is given by

$$\Delta V_{tide} = 3\pi G \rho a \cos\alpha \sin 2\phi \tag{1}$$

where a is the orbital semi-major axis and ρ is the (local) mass density of the stratified Galactic disc, the directional parameters ϕ and α corresponding respec-

tively to galactic latitude and the angle between the orbital plane of the comet and the plane which contains the Sun-comet line and is perpendicular to the Galactic plane (Fernandez *loc. cit.*). The effect of ΔV_{tide} is to have some fraction of the Oort cloud comets regularly deflected towards the planetary system where they may experience planetary perturbations and become part of the observable flux of comets at 1 AU from the Sun. To examine variations in the cometary flux as the Sun changes its vertical position z in the Galactic disc, the vertical tide $T \propto \Delta V_{tide}$ is expressed here in the form

$$\mathrm{T} = -4\pi \mathrm{G}\rho(\mathrm{z})\Delta \mathrm{z} \tag{2}$$

where Δz is the instantaneous difference in the height above the plane (z=0) between Sun and comet, and $\rho(z)$ is the effective mass density of perturbers responsible for the tide at z. This 'tidal' background of perturbers then yields, through changes of orbital angular momentum, a temporal flux of near-parabolic comets into the planetary system given by

$$\dot{\mathrm{N}} = \int \dot{\mathrm{n}}(\mathrm{a})\, \mathrm{da} \tag{3}$$

where the flux from comets with semi-major axes a ($a_l \leq a \leq a_u$) may to sufficient approximation be written as (Bailey 1986)

$$\dot{\mathrm{n}}(\mathrm{a}) = \mathrm{A}\mathrm{a}^{\gamma - 9/2}\mathrm{g}(\mathrm{a}) \tag{4}$$

where $g(a) = (a_l/a_u)^{7/2}$ for $a \leq a_T$ but is otherwise unity. Here A is a constant, the population of comets is distributed as $(\mathrm{energy})^{-\gamma}$ and the loss cone is filled beyond a variable 'tidal distance' a_T.

If a_{T0} represents the critical semi-major axis at z=0 and a_T is that at some other height above the plane, then (Bailey 1986)

$$\mathrm{a_T} = \mathrm{a_{T0}}[\mathrm{d(z)}]^{2/7} \tag{5}$$

with $d(z) = \rho(0)/\rho(z)$, whence $\dot{N}$ may be represented as

$$\dot{\mathrm{N}} = \dot{\mathrm{N}}_0(\mathrm{a} \leq \mathrm{a_{T0}})\mathrm{d(z)}^{-1} + \dot{\mathrm{N}}_0(\mathrm{a} \geq \mathrm{a_{T0}})\mathrm{d(z)}^{1-2\gamma/7} \tag{6}$$

where $\dot{N}_0$ denotes the contribution to the comet flux as the Sun crosses the galactic plane. Fig. 1 illustrates the differential flux due to the galactic tide for various Oort cloud models ranging from the classical one (γ=2.5) to modified ones with a strong central condensation ($0.5 \geq \gamma \geq -2$): the critical semi-major axis a_{T0} has been taken equal to 20,000 AU but this is not critical to the discussion. It can be

seen that the first term in eqn. (4), describing the flux of comets with $a \leq a_T$, is generally dominant, irrespective of the structure of the Oort cloud. Thus the smooth tidal component yields a cometary flux, into the planetary system, which is to a first approximation linear with the applied tide, varying as

$$\frac{\dot{N}(z)}{\dot{N}(0)} = \frac{\rho(z)}{\rho(0)} \tag{7}$$

The expected amplitude and period of any galactic cycle are thus in principle predictable from eqn. (7), given a knowledge of the solar orbit and environment, while a contemporary increase in the LP comet flux is also anticipated due to the latest *approach* to a solar crossing of the Galactic plane $\sim 2.5 \pm 2$ Myr BP.

There is a clear prediction based on eqn (1) of a LP comet flux whose aphelion distribution diminishes to zero at the Galactic equator and poles due to the influence of the vertical tide. Such an effect is observed to be present (Delsemme & Patmiou 1986) albeit affecting some 50% of the Oort cloud flux. It follows that one can be reasonably certain of a significant contribution to the cometary flux as a result of the vertical tide close to the Galactic plane; not however discounting an equally significant contribution to the LP comet flux as individual bodies (*e.g.* stars) from the Galactic environment individually penetrate the Oort cloud and impulsively perturb comets in the neighbourhood of their tracks (see Section 4; *cf* Yabushita 1989).

According to Bahcall & Bahcall (1985), the half-period of the Sun's vertical motion may lie in the range 26-37 Myr, with maximum vertical excursions in the range 49-93 pc. The longer periods were obtained for models in which a spheroid of half-height 700 pc contained substantial unseen material. However Gilmore & Wyse (1987), from an analysis of K dwarfs at the south galactic pole, find no evidence for significant hidden mass beyond ~100 pc. The likely range of solar half-periods is then found to be 26-32 Myr, with vertical amplitude in the range 50-82 pc. The greater amplitudes are associated with the longer periods, and the motion is simple harmonic to a high degree of approximation.

The distribution of stars in the solar neighbourhood is commonly described in terms of (i) a current spiral arm distribution of molecular clouds and young stars with half-height σ_z ~50 pc and vertical velocity dispersion $\sigma_w \sim 5$ km s^{-1} (say); (ii) a more evenly spaced young population (manifested by A and F stars) with σ_z ~100 pc and σ_w ~7 km s^{-1}; and (iii) a merging of older components with σ_z ~250 pc, σ_w ~20 km s^{-1}. If the primary contribution to the tide comes from a dark matter distribution similar to the first two populations, then to a sufficient approximation one may model the local disc by an exponentially declining population of vertical density amplitude $Z_{1/2} \sim$ 50-100 pc. For a vertical amplitude

of 50 pc in the solar orbit, the long-period comet flux is then expected to have a periodicity ~26 Myr with a peak-to-trough amplitude in the approximate range ~1.5 to 4.0 (*cf.* Matese *et al.* 1995). A solar motion of amplitude 80 pc yields a periodicity ~32 Myr with amplitude in the range ~2.2 to 5. If these variations in comet flux are reflected in terrestrial signatures (Section 6), a strong periodicity in geological phenomena is certainly to be expected. The flux variations under these circumstances are primarily due to the change in tidal radius, the loss cone being permanently filled beyond a_T ~20,000-35,000 AU.

The characteristic infall time of a long-period Oort cloud comet is ~2 Myr. Once thrown into the loss cone, the passage time t_σ from an orbit with perihelion $q \sim 10$ AU say to sub-Jovian space may be obtained from the diffusion equation of van Woerkom (1948). This yields t_σ ~1 Myr, comparable with the timescale $\lesssim$1 Myr, obtained in numerical trials (Bailey *et al.* 1994), for the transfer from distant chaotic orbits in the Solar System to Earth-crossing ones. Since the physical lifetime of a comet in an Earth-crossing orbit is several orders of magnitude less than its likely dynamical one, it represents a negligible addition to the diffusion time. Thus the phase lag between a significant change in galactic tide, and that of the comet flux in the inner planetary system, is typically 3 ± 0.5 Myr. Since the Sun crossed the Galactic plane 2.5 ± 2 Myr BP, it appears that the Earth should currently be at or near the peak of a geologically disturbed epoch; this does indeed seem to be the case (as illustrated, for example, by the onset of the Pliocene epoch ~5 Myr BP and of the Pleistocene glaciations $\sim$ 2.5 Myr BP). Some aspects of this disturbed epoch however are likely to be correlated with Gould's Belt as much as with the Galactic plane crossing.

4 Impulsive perturbations of the Oort cloud

Galactic disc material disturbs the Oort cloud both smoothly, through the adiabatic tide, and stochastically, through penetration by individual gravitating bodies, effectively generating a sequence of mini-showers. The impulses generated by such invaders may reach a peak during Galactic plane passage where the density of material is greatest, and so add to the effect of the adiabatic tide. The flux of comets in such a shower or mini-shower may be calculated from (Fernandez 1992)

$$\dot{n}_c \sim 2\pi[r^3\gamma(r)F_L/P]\int_0^\infty D_L^2(h^2+D_\odot^2)^{-3/2}dh \tag{8}$$

The symbols have the following meanings: h represents the perturber's distance, along its trajectory, from the impact parameter $D_\odot$; $\gamma(r) \propto r^{-(\alpha+2)} \propto a^{-\alpha}$ is the

number density of supposedly thermalised comets (semi-major axis a and perihelion distance q); $2F_L^{1/2} = 2(2q_L a^{-1})^{1/2}$ is the angular radius of the normal 'loss cone' associated with each comet-Sun direction; $q_L \sim a_{Jupiter} \sim 6$ AU is the presumed perihelion distance below which it is clear that planetary perturbations are most likely to deflect loss-cone comets towards short-period orbits (*cf* Fig. 8.3 of Bailey *et al.* 1990) where they have the greatest influence on the Earth; and $P \propto a^{3/2}$ is the orbital period corresponding to the most intense phase of the cometary shower.

In accordance with this formulation, D_L is the radial cross-section of a cylindrical volume along the perturber path (narrowest at the point of closest approach) within which Oort cloud comets are most effectively deflected into the loss cone. Now, on the impulse approximation, the deflection δv suffered by a comet due to a perturber passing at distance D with velocity V is $\delta v = \frac{2Gm}{DV}$. One then finds that eqn (8) yields a mini-shower flux

$$\dot{n}_c \propto \rho a^{2.5-\alpha} \int_0^\infty (m/V) f(V) dV \tag{9}$$

where $[\rho/m, f(V)]$ are respectively the number density and velocity distribution of sporadic perturbers.

Monte Carlo simulations were carried out in which the Sun was imagined to orbit through a field of perturbers with a Schwarzschild velocity distribution:

$$f(V) = \frac{h_u h_v h_w}{\pi^{3/2}} \exp -[h_u^2(u-u_\odot)^2 + h_v^2(v-v_\odot)^2 + h_w^2(w-w_\odot)^2] \tag{10}$$

An example of the resulting comet flux is shown in Fig. 2a, corresponding to the motion of the Sun through a population of brown dwarf stars ($M = 0.05 M_\odot$) with an extreme Population I distribution. Typically several hundred such dark matter stars could pass through the Oort cloud every million years, and it can be seen that the cumulative effect of the mini-showers so produced may readily yield comet flux cycles with amplitudes of order 4:1.

There is also the possibility that such perturbers would generate a second flux cycle, out of phase with the first. If the Sun drifts with velocity $V_\odot$ through an isotropic, maxwellian field of one-dimensional velocity dispersion σ, then the mean square diffusion coefficient J_2 for the angular momentum of comets at distance r from the Sun, due to 'stochastic' as opposed to 'tidal' loss cone filling, is given by

$$J_2 = B(m,n) r^{7/2} \frac{\Phi(x)}{x} \ln(\Lambda) \tag{11}$$

(Heisler & Tremaine 1986, Spitzer & Hart 1971) where $x = V_\odot/(2\sigma)$, Φ is the error function, $\Lambda = aV_\odot^2/GM_\odot$, and $B(m,n)$ is a constant proportional to the

mean square mass and number density $n(z)$ of the perturbers. It follows that as $V_\odot$ declines, J_2 increases; and hence the comet flux is enhanced around the vertical extremities of the solar orbit, yielding a second oscillatory cycle a half-period out of phase with that induced by the Galactic tide. The amplitude is relatively small, amounting to only a few percent even when the perturbing bodies have stellar masses. Eqn (6) holds only for a spherical velocity distribution of perturbers. Monte Carlo simulations employing various 'flattened' velocity distributions revealed, however, that out-of-plane oscillations of 10-20% could be attained if the dark matter perturbers had an extreme ~~p~~Population I velocity distribution. This might be detectable in a very complete geological record.

Simulations based solely on eqns. 9 (~~10~~) and 10 (~~11~~) may not be the whole story, however. Regular out-of-plane excitation of the inner Oort cloud by potential dark matter perturbers having low mass m and velocity v, ostensibly associated with the principal distribution of young, star-forming material in the Galactic plane (*cf* Section 3), poses important questions as to the precise location, distribution and motion of such material in the neighbourhood of the Oort cloud as the Sun travels along its Galactic orbit.

Thus the theoretical concepts of a 'local standard of rest' (coupled with an arbitrary velocity ellipsoid), and 'infinite plane parallel disc' may not adequately represent the contemporary Galactic environment. For example, by using early type stars and HI as Galactic tracers, it has long been recognized that the Sun lies just within the radial distance of the inner boundary of the Orion spiral arm as delineated by OB associations and HII regions, albeit this boundary is ill-defined locally because the Sun is also immersed in a particular OB association known as Gould's Belt, having the appearance of a spur or fin protruding from the Orion spiral arm (*e.g.* Sharpless 1965, Olano 1982). Furthermore, by making use of the slightly older A stars to represent the youngest ($\lesssim 500$ Myr) and nearest ($\lesssim 100$ pc) extended stellar systems pervading this environment, it has also long been recognized that the solar neighbourhood is penetrated by several dominant 'moving groups' (Eggen 1965). Of these interpenetrating systems, the Ursa Major (or Sirius) and Hyades Groups are the most prominent 'intermediate age' examples while the Pleiades (or Gould's Belt) and Coma Berenices (or Orion Arm) Groups are broadly representative of B stars within 300 pc (Eggen 1961) and hence of the youngest and most massive configurations currently pervading the wider solar environment.

But while these groups are additive in such a way as to define a local standard of rest (LSR), albeit approximately and with non-standard (deviated) velocity ellipsoids, both the A stars and B stars are notably deficient at the (HI) LSR. It follows that the HI and stellar LSR around the Galaxy is essentially a statis-

tical rather than physical attribute of the immediate environment and does not necessarily coincide, even locally, with spiral arm motion. This is not of course important when all that is required is a *conventional* standard of rest but there have been attempts in the past to make use of a more specific statistical entity such as the local spiral arm by defining a (so-called) basic standard of rest in terms of a common velocity distribution *mode* (*e.g.* Vyssotsky & Janssen *et al.* 1951). These attempts were essentially abandoned when the moving groups were accurately specified and it came to be seen that the BSR was merely an approximation to the Coma Berenices Group motion ($\{u, v, w\}_\odot = \{-5, -5, -7\}$ km s^{-1}) possibly corresponding to the nearest spiral arm. Abundance considerations indicate a clear affinity between the Coma Berenices and Ursa Major Groups as well as the Sun despite marked differences of age (Eggen 1965); and a separate affinity between the Pleiades and Hyades Groups. The question arises whether these characteristics broadly reflect separate dynamics for the two neighbouring spiral arms according to their differing galactocentric distances. If so, we may suppose that the Sun is essentially guided by one massive spiral arm and simulate the instantaneous velocity distribution of underlying dark matter perturbers by a group motion reflecting the material distribution in the arm when its initial condensations uncouple from the gas. Comparison with young groups and associations suggests that the internal velocity dispersion of such young material may be very small, of order 2 km s^{-1} or less in one dimension (Blaauw 1990).

Detailed investigation of the phase distribution of the A stars in the vertical column centred on the Sun (Jones 1962, Woolley 1965) provided the first (early) indication of a significant overdensity (*i.e.* dark matter) in the local spiral arm, the latter being treated as a plane stratified tube with a rectangular cross-section. It is therefore possible that the Sun is immersed in, and virtually co-moving with, a local spiral arm population containing a significant proportion of low mass dark matter. If the latter comprised black dwarves (*alias* brown dwarves or machos) of $\sim 0.05 M_\odot$, then perturbations of the Oort cloud would maximize at the vertical extremities of the Sun's orbit, when $w_\odot = 0$ km s^{-1}; in order not to be overwhelmed by random stellar perturbations, the bulk of the perturbed comets would then have to come from a dense inner cloud infrequently penetrated by stars ($\gamma \gtrsim 4$; *e.g.* Hills 1981). Fig. 2 (b) illustrates the flux variations obtained in a simulation of this model. The expected phase $\phi \sim P/2 + t_c - t_i - t_d$ where t_c represents the time of last crossing of the Galactic plane, P is the half-period of the solar vertical oscillation, t_i is the infall time of a comet from the inner core and t_d represents the diffusion time within the planetary system. With $t_c \sim 2.0 \pm 0.5$ Myr, $P/2 \sim 13.3 \pm 0.3$ Myr, $t_i \sim 1.3 \pm 0.3$Myr and $t_d \sim 1$ Myr, then $\phi \sim 13.0 \pm 0.7 Myr$ BP, which is within 1 or 2 Myr of that observed (Table I). The adopted value of

t_i is an average for the periodic value of the comets involved assuming that they remain in the loss cone for two orbits before experiencing a planetary perturbation.

Further independent evidence for a recent, massive spiral arm of this nature would of course need to be sought before an explanation of this kind for the terrestrial record could be accepted, but the kinematics of the Sun relative to the Orion spiral arm are suggestive also of a longer-term epicycle parallel to plane *and* arm, possibly consistent with $\sim$100 and $\sim$200 Myr cycles in the terrestrial record (Clube & Napier 1986). Should the search be successful, it is possible that any future theory of the origin of spiral arms would require *primary* condensations in the form of black dwarves or machos. The stellar kinematic, cometary and terrestrial data would then provide us with an interesting new constraint on the process of star formation.

5 The nature of the comet-Earth interaction

The idea that prompt mass extinctions of life might arise from stray asteroid or comet impact has a long history, but it was not until the discovery of a substantial Earth-crossing asteroid population that a quantitative hypothesis could be developed (Napier & Clube 1979), while the discovery of iridium-rich deposits at the Cretaceous-Tertiary boundary appeared to confirm the hypothesis at one mass extinction horizon (Alvarez *et al.* 1980). The hypothesis has recently received further support with the discovery of the 180 km Chicxulub crater and associated tektite debris in the Caribbean, the age 64.98$\pm$0.06 Myr closely coinciding with a catastrophic shift in the flora of the Western United States, and with the mass extinction of ammonites at the KT boundary.

Impacts have also been proposed as an astronomical trigger for other geological processes, such as geomagnetic reversals (Hoyle 1981, Clube & Napier 1982, Muller & Morris 1986). Thus it has been suggested that impacts might frequently affect the growth and decay of polar ice caps. If so these would, through altering the Earth's moment of inertia, lead to disturbances or reversals of the geomagnetic field (*e.g.* Olausson & Svenonious 1975; Doake 1977). Correlations between global ice volume and fluctuations in the Earth's magnetic field have been claimed to support this proposition (*loc. cit*). However a problem with a pure impact hypothesis, for field reversals and other geological phenomena, is that a significant perturbation of the underlying geological processes often seems to require a more prolonged application of stress than would be expected from a single large impact; the growth time of a polar ice cap, for example, is several 10^3 yr, as against a stratospheric residence time of only a few months to several years for $\gtrsim$sub–

micron dust particles.

In the Galactic hypothesis as developed by the authors, the injection of dust into the stratosphere is associated with the variable influence of meteoroidal debris ($\sim 0.1\mu$m–10 km) deriving from the intermittent arrival (0.1–10 Myr), sojourn (0.01–0.1 Myr) and hierarchical breakup of rare, very large comets (radius $\gtrsim 50$ km) which have been thrown into short-period orbits from the classical Oort cloud (Hoyle 1984; Clube & Napier 1984, 1986 a,b; Clube 1987; Napier 1987, 1993). The probable debris from one such comet has been identified in the contemporary environment (Clube & Napier 1984, Steel *et al.* 1994), and there may be a surviving nucleus: both Chiron (Hahn & Bailey 1990) and an unseen librating source in the 7:2 resonance with Jupiter (Asher & Clube 1993) have been proposed for this. The disintegration of a $\sim$100 km diameter comet in an Apollo-like orbit would, over a few 10^4 yr, yield an average annual dust influx of $\sim 5 \times 10^6$ tons into the stratosphere, generating an intermittent atmospheric dust veil of optical depth $\sim$0.1–1 capable of inducing major perturbations of the Earth's climatic system. In addition to impact signatures from $\gtrsim$ km–sized fragments, relatively undiluted material may infall for a period $\gtrsim 10^4$ yr, comparable with the growth time of a polar cap. Over such a period, assuming a chondritic abundance 5×10^{-7} in comet dust, iridium deposition rates of $\sim 10^{-2}$ ng cm^{-2}yr^{-1} are likely (Clube & Napier 1987). Thus in general, during a period of high comet flux, environmental deterioration caused by a series of sharp climatic coolings may compete with the prompt effects of large impacts. Both extinction mechanisms and geophysical signatures at extinction boundaries are therefore likely to be complex and to show the effects of multiple impacts and prolonged dust deposition rather than simple one-off impact (Clube & Napier 1982, 1984, 1986; Bailey *et al.* 1995).

There is indirect evidence for a relationship between such relatively prolonged astronomical inputs, and terrestrial trauma such as climatic disturbances, mass extinctions and geomagnetic reversals: (i) the latter are associated with three of the five tektite age groups. In particular the creation of the 10 km Bosumtwi impact crater occurred 8,000–30,000 yr *after* the Jaramillo geomagnetic reversal of 900,000 BP, and that of the Australasian tektites occurred 12,000 yr *before* a reversal at 730000 BP (Schneider & Kent 1990), the chance probability of these near–synchronicities being $0.002 \lesssim p \lesssim 0.009$. Associations with reversals have also been claimed for the Ries crater 15 Myr BP and for the KT boundary. (ii) An association between reversals and climatic events seems to be well established at least for the Upper Pleistocene (Doake 1978; Burek & Wanke 1988). (iii) The probable occurrence of multiple impacts at the KT boundary (Alvarez & Asaro 1990) is likewise consistent with a giant comet disintegration; while (iv) the discovery of amino acids of probable extraterrestrial origin spanning $\sim$1 m above

and below the Stevns Klint KT boundary (Zhao & Bada 1989) may be understood as a low-temperature accretion of cometary dust over $\sim 10^5$ yr (Bhandari 1991), but not as material processed through a $\sim 10^5$ K fireball (Clube & Napier 1990, Zahnle & Grinspoon 1990).

6 Cyclicity in geological events

In recent years many attempts have been made to derive periodicities from modern geological data but such factors as the use of filters (moving windows), the presence of secular trends, and the lack of a viable mechanism, have cast doubt on the results obtained and caused the issue to remain unsettled. The incompleteness of the geological record has been a further handicap.

Recently, however, a more comprehensive geological time series covering the past 260 Myr has become available (Rampino & Caldeira 1992), and in the present Section we analyse this new dataset by applying periodogram analysis to the unfiltered data. The periodogram has the simplest statistical behaviour of the various period-hunting techniques in use (Scargle 1982), and has the potential to detect even faint signals in noisy data (Horne & Baliunas 1986). There are, however, well-known problems associated with its use. For example the secular trends in a non-stationary time series may dominate the form of its power spectrum, and their neglect may both yield spurious 'periodicities' and obscure other signals which may be present (*e.g.* Chatfield 1984). In addition the technique is intrinsically noisy, the relative variance $\sigma(\mathrm{I})/\mathrm{I}$ of the power I being unity irrespective of the numbers of data; thus high spurious peaks can occur even in random data (Bartlett 1962; Scargle 1982). We meet these potential difficulties, and test the reality of any derived periodicities, by a differential technique: the power spectra of the real data are compared with those of synthetic, random data having the same broad, underlying probability distributions as the real data. Any significant differences between the real and synthetic data can then only be due to some property of the real data on a timescale short compared with that characteristic of the randomization procedure.

The hypothesis that a Galactic periodicity exists in the terrestrial record is here tested against the null hypothesis that the data are random, independent and drawn from a distribution similar overall to that observed. Another null hypothesis might be that there is no periodicity as such, but an 'episodicity', that is a tendency for the phenomena to have say a gamma distribution, recurring on a characteristic timescale; we do not investigate this possibility here since at present no theory quantitatively predicts it. Both edge effects and secular trends (nonstationarity)

in the underlying distribution have the potential to generate spurious 'periodicities' in the power spectrum, and must be allowed for.

6.1 Biosphere and crustal phenomena

Rampino & Caldeira (1992) analysed their 260 Myr dataset for periodicities and concluded that a ~26.6 Myr periodicity is present. Their compilation encompasses mass extinctions, anoxic events, the deposition of evaporites, flood basalt outpourings, sea-floor spreadings, geological sequence boundaries and orogenic events. Impact crater formation and geomagnetic reversals were not considered by them. We tested all these events for periodicity, our statistical treatment differing from that of Rampino & Caldeira in that (i) we tested the a *priori* galactic hypothesis rather than search for periodicities *ab initio*; (ii) we used unfiltered data to avoid the possibility of window artefacts; and (iii) we took account of edge effects and secular trends which might otherwise introduce spurious periodicities.

The data listed by Rampino & Caldeira included 11 mass extinction peaks found by Raup & Sepkoski (1984), and these were examined separately, using a simple wrapping correction to allow for edge effects (Lutz 1985). Thus over a range of frequencies the power $I = 2R^2/N$ was calculated, R being the magnitude of the vector sum of the N unit vectors

$$\mathbf{e_i} = \mathbf{e_x} \sin(2\pi t_i/P) + \mathbf{e_y} \cos(2\pi t_i/P)$$

obtained in a circular transformation of the data t_i for the trial period P. This procedure revealed a modest peak at 26.7 Myr, consistent with a periodicity of this length, as previously claimed by Raup & Sepkoski (1984).

The statistical significance of the derived cycle was evaluated by adding, to each of the 11 mass extinction epochs of the past 245 Myr, a random number in the range (-50,+50) Myr, evaluating the maximum power in the range (26,37) Myr permitted by the Galactic forcing hypothesis, and repeating the power spectrum analysis. This procedure was carried out 500 times. The random numbers added were small enough to maintain the overall temporal distribution of the events but large enough to smear out any periodicity in the range of interest. It was found that the random data yielded spurious periodicities of at least the 'observed' strength in 51 trials of synthetic data, whence the periodicity was confirmed only at the 90% level. Trials in which the random numbers were in the range (-25,+25) Myr yielded no discernible difference.

The phase, however, corresponded to a last peak at 8.0 Myr BP, whereas eye inspection of the complete geological record (Fig. 3) reveals the presence of an anomalous, near-contemporary surge of geological activity (consistent also with

the Pleistocene glaciation of $\lesssim 2.5$ Myr BP although this was not included in the compilation). The analysis was therefore repeated, excluding the extinction peak at 1.6 Myr listed by Rampino & Caldeira. The remaining 10 data points yielded a periodicity $P \sim 25.9$ Myr, phase $\phi \sim 12.1$ Myr whose significance was found from 500 Monte Carlo simulations to be ~99.8%.

The remaining geological data were analysed in similar fashion, and yielded a periodicity $P \sim 26.3$ Myr, phase $\phi \sim 10.8$ Myr at a confidence level ~99.4% (from 500 trials) when data <10 Myr BP were excluded. This solution is remarkably stable to progressive truncation of the data (Fig. 4). Rampino & Caldeira argued that because of better dating the more recent data (to 140 Myr BP) yielded a stronger periodicity, and this too was confirmed. It is remarkable that the periodicity is nearly half a cycle out of phase with Galactic plane crossings by the Sun.

If some of the major geological events were interrelated, these formal significance levels would be somewhat reduced. A comprehensive geological study of all the events would be required to quantify this possibility; but it appears nevertheless that the periodicity is confirmed at a fairly high confidence level. The surges appear to be remarkably strong, with global Earth processes effectively switching on and off (Fig. 3). Thus the specific hypothesis apparently being confirmed at this confidence level is one in which the *whole Earth* is affected by the Galactic environment: in particular, mass extinctions of species and genera are simply part of a broader cyclical pattern affecting many geological phenomena.

6.2 Impact craters

Following the claim by Raup & Sepkoski (1984) that a ~26 Myr periodicity exists in the marine extinction record, the question of whether a similar periodicity exists in the terrestrial impact cratering record was taken up by several groups (Seyfert & Sirkin, in 1979, had already claimed that the impact record revealed the existence of 'impact epochs' separated at 26 Myr intervals; *cf* the 'bombardment episodes' of Napier & Clube 1979). Some workers have claimed that a periodicity of ~30 Myr exists at about the 99% significance level (Rampino & Stothers 1984, Alvarez & Muller 1984, Yabushita 1991, 1992), while others have argued that it exists only at a confidence level of ~90% (Tremaine 1986, Grieve & Shoemaker 1995) or that there is no periodicity at all (Weissman 1990).

These studies generally suffer from a failure to allow for edge effects and secular trends, which may induce spurious periodicities (Lutz 1984). In addition several of them employ age data with dispersions up to ~20 Myr, although the detectability of a period declines sharply as σ/P increases: a 26 Myr periodicity (say) is virtually

undetectable in even a large dataset where $\sigma \sim 20$ Myr. Further, the confidence level C of any signal detected depends strongly on the hypothesis being tested. The question: 'Is there a periodicity in the cratering record?' may yield a quite different C from: 'Is there a Galactic periodicity (26–37 Myr) in the record?' However, given the hypothesis under discussion, a much more targeted question is appropriate: 'Is there a periodicity $P = 26.3 \pm 0.5$ Myr, $\phi = 11.0 \pm 1$ Myr in the impact cratering record?'

To investigate the latter question, the dataset of Grieve & Shoemaker (1994) was culled, the criteria for inclusion being that the craters were $\geq$10 km in diameter, and that their ages were $\leq$200 Myr, measured to a formal precision $\sigma \leq 10$ Myr. The 10.5 km Bosumtwi crater of age 1.03 Myr was excluded from the list as the parent bolide was iron and presumably non-cometary in origin. The 30 remaining impact craters are listed in Table I. Power spectrum analysis was applied to this set (see Fig. 5) excluding craters <10 Myr old to take account of the recent out-of-phase upsurge apparently revealed by the geological data.

The peak power I is found to be ~6.0, which is a relatively weak signal. Thus the question: 'Is there a periodicity in the record?' is affirmed at only a ~95% significance level. However the period and phase are, within the errors, identical with those of the combined Rampino/Caldeira (RC) data. Thus for the impact craters:

$$P = 27.0 \pm 0.3 \text{ Myr}, \phi = 11.1 \pm 0.7 \text{ Myr},$$

while for the RC data:

$$P = 26.3 \pm 0.4 \text{ Myr}, \phi = 10.8 \pm 1.0 \text{ Myr}.$$

The coincidence is significant at a confidence level ~99.4%. Thus, although the cratering periodicity is weak, it is present and it correlates with the geological surges at a high level of significance. The signal appears to be dominated by three main bombardment episodes, which occurred ~39, 65 and 93 Myr BP.

The existence of this signal confirms that global terrestrial processes are subject to external forcing. However the periodicity in the cratering record is much weaker than that in the geological one, which suggests that large-body impacts may be a contingent process rather than the prime cause of global geological stress. It is likely that a strongly variable cometary component in the impact cratering record (say 3:1 or 4:1 in amplitude) is diluted by random contributions from $\gtrsim$1-km Earth-crossers derived from the asteroid belt; thus large-body impacts seem inadequate on their own to produce the strong cyclicity observed in evolution and geology. The suggestion that small terrestrial craters reveal a stronger periodic signal than large ones (*e.g.* Yabushita 1992) would be in accordance with smaller cometary debris being the prime cause of global geological stress. The latter proposition is further supported by a deep-sea sedimentary record of ^{3}He deposition, of

probable cometary origin, covering the last ~72 Myr (Farley 1995). The helium deposition shows strong peaks at ~66 Myr, ~38 Myr, ~8 Myr and $\lesssim$ 2 Myr, consistent with the Galactic hypothesis described herein though, like the geomagnetic reversal record (Section 6.3), there is also a peak at ~50 Myr. However the pattern of helium deposition is quite different from that of iridium deposition, while the ~38 Myr episode correlates with several tektite events; the latter led Farley (1995) independently to propose the occurrence of 'multiple terrestrial impact events associated with dust-bearing objects.' Higher resolution examination of the dust deposition reveals a 100,000-year cyclicity in the ^{3}He deposition which correlates positively with the 100,000-year climatic cycle (Farley & Patterson 1995); the latter may incidentally reflect a cyclic variation in comet capture probability matching the 'grand cycles' due to simple multiples k_j (j=5,6,7,8) of the planetary secular resonances (g_j, s_j) (Knesevic *et al.* 1991). Thus the cratering periodicity, coupled with the sedimentary data, appear to support the hypothesis that large comets are periodically thrown out of the Oort cloud, dusting the stratosphere and so producing terrestrial effects through climatic forcing.

6.3 Geomagnetic reversals

No detailed theory of the geomagnetic dynamo exists. Nevertheless a ~30 Myr cycle has frequently been claimed to exist in the geomagnetic reversal record (*e.g.* Negi & Tiwari 1983, Raup 1985), as have significant correlations between impact signatures and reversals (Section 5). Further, a modest impact ($\sim 10^{17} g$), or a sudden change in the Earth's spin rate induced by enhanced polar ice consequent on stratospheric dusting, may yield substantial velocity perturbations at the core-mantle boundary. The fluid motions associated with the dynamo action would thus be strongly disturbed (Clube & Napier 1982; Pal & Creer 1986; Muller & Morris 1986). According to Creer & Pal (1989), if impacts affect the operation of the geomagnetic dynamo, they probably do so by modulating reversal rates already prescribed by core-mantle processes. Epochs (superchrons) when the reversal rate is high ($\gtrsim 100\,\mathrm{Myr}^{-1}$) appear to alternate with intervals when the field polarity is fixed.

Mazaud *et al.* (1983) claimed that the reversal record of the present superchron (the last 70–80 Myr) showed an approximate 15 Myr periodicity, the Raup periodicity being in phase with it. Creer & Pal (1989) applied maximum entropy analysis to the record going back 150 Myr, and found two periodicity peaks, at ~15 and ~30 Myr, the former being the stronger. These cycles have been interpreted as artefacts due to data binning (McFadden 1984) or time series non–stationarity (Lutz 1985, Lutz & Watson 1988). Indeed, the geomagnetic reversal record is dom-

inated by a strong secular increase with time over the last 80 Myr. However, the cycles remain robust with regard to variations in window size and record length (Mazaud *et al.* 1984, Creer & Pal 1989), while peaks occurring at $\sim$15 and 30 Myr intervals are readily seen by eye (Fig. 5). In order to assess their significance, it is necessary first to disentangle the artefacts created by the secular trend and the edge effects; this is achieved through the Monte Carlo procedure described above.

For consistency, reversal data younger than 8 Myr were first excluded from the analysis, and a power spectrum derived, with the data weighted to correct for edge effects (Lutz 1984). However it was found that the solution obtained was sensitive to the precise correction applied for the extremely strong secular trend: excluding data younger than 5 Myr rather than 8 Myr, or older than 70 Myr rather than 80 Myr, produced appreciable shifts in the derived period and phase of the signal. Thus by reasonable adjustments in the edge correction procedure a periodicity could be obtained anywhere in the range $26 \lesssim P \lesssim 34$ Myr, with the corresponding phase in the range $12 \lesssim \phi \lesssim 15$ Myr. Although imprecisely determined, the Monte Carlo trials revealed that the hypothesis of Galactic periodicity was preferred over that of random production at a confidence level of $\sim$99.8%. Surges in the reversal rate are also allowed by these trials which are consistent with the biosphere, crustal and impact cratering data peaks, albeit interleaved with weaker surges during the variable polarity superchrons.

Fig. 5 seems to reveal the presence of a persistent $\sim$15 Myr cycle. Monte Carlo simulations (3000 of them) revealed that this arose by chance in less than 1 percent of trials; moreover, the cycle appears to have a characteristic weak–strong structure. The $\sim$15 Myr periodicity is found also to be continuous with three surges of reversal activity over the period 120–165 Myr BP. These results do not establish a $\sim$13 Myr periodicity in the geomagnetic record as against say episodicity, or even a $\sim$26 Myr cycle with random, episodic surges: the periodicities were being tested against the null hypothesis of a random (Poisson) process, whereas the underlying mechanism might be non Markovian in nature. However, a Poisson process is consistent with the likely instability of the geomagnetic dynamo (Ito 1980) and with the Poisson distribution of intervals between reversals (Cox 1969); there is thus a *prima facie* case that the geomagnetic dynamo is affected by Galactic processes, perhaps through stresses at the core surface induced by rotational changes (Clube & Napier 1982, Pal 1989) which correlate with the incidence of glaciations and the arrival rate of giant comets.

The main conclusions of this Section are summarised in Table I.

7 The phase of the cycle and the solar orbit

Taking the per-genera mass extinctions as listed by Sepkoski (1989), the mean absolute deviation from a periodicity of 25.9n+12.0 Myr is 3.3 Myr, with no sign of a secular drift (the mean absolute deviation of one interval from its neighbour is 4.1 Myr). However, as we have seen, there is good empirical evidence for a recent, strong outburst of geological activity within the last $\lesssim 5$ Myr. This outburst appears to be real rather than an observational artefact as it includes, for example, the Pliocene as well as three of the 14 mountain-building events of the last 260 Myr, and also the onset of the Pleistocene glaciation ~2.5 Myr ago. Its occurrence is also consistent with the recent passage of the Sun through the Galactic plane.

In the context of the Galactic theory, there appear to be two distinct possibilities for the observed phase difference overall between the peaks of terrestrial disturbance and the solar crossings of the Galactic plane. Either the in-plane peaks are dominant and there has been a recent $\sim \pi/2$ shift in phase of the Sun's orbit, or the out-of-plane cycle is in fact the dominant one. Arguments can be given for and against these alternatives:

Kinematically, the Sun is a B star, whose galactic orbit therefore has a relaxation time of $\lesssim 200$ Myr (Binney & Tremaine 1987). The chief perturbers are giant molecular clouds and spiral arms; relaxation thus occurs, in the main, in discrete jumps during close encounters with such large masses, rather than primarily through steady diffusion. It appears that the Sun passed north to south through or close to the Orion spiral arm ~13 Myr ago, on a shallow trajectory, and in addition crossed the expanding gas ring of the Gould Belt system about 10.0 ± 0.2 Myr ago (Olano & Pöppel 1987). This complex has a mass $\sim 10^6 M_\odot$, and the penetrating encounter could well have yielded a velocity perturbation $\Delta w \sim$7–10 $\mathrm{km\,s^{-1}}$ sufficient to yield the required phase shift. This solution meets no obvious astrophysical or dynamical problems, but it does require that the phase shift was coincidentally close to $\pi/2$.

On the other hand, the proximity in velocity space of the Coma Berenices Group may arise because the Orion (dark matter) spiral arm essentially controls the v-motion of the Sun as well as its 'uncoupled' u- and w-epicycles (Woolley 1965). Under these circumstances, the Sun passed north to south through the Orion spiral arm ~27 Myr ago, but the subsequent dynamical influence of Gould's Belt (and the resulting phase shift) is assumed to have been modest. In that case we expect recent evolution on Earth to be dominated by ~26 Myr out-of-plane peaks due to low-velocity perturbers, ~26 Myr in-plane peaks due to the Galactic tide and perhaps longer-term amplifications of the terrestrial response during successive penetrations of the Orion spiral arm. While this solution obviates the need for any

recent phase shift, it does require the velocity dispersion of the perturbers to have been remarkably small for over $\gtrsim$200 Myr say (Figs. 2b and 3); this might imply that the dark matter bodies are small, dense, evanescent molecular clouds.

8 Discussion and Conclusions

Thirty million year cyclicities (the Holmes cycle) have been claimed to exist in orogenies, sea level, climate, geomagnetic reversals and mass extinction events. Some of these claims go back at least 70 yr (Holmes 1927, McCrea 1981, Clube & Napier 1986), and many workers over this period have commented on the proximity of the cycle to the half-period of the solar vertical motion. A mechanism for inducing galactic periodicities in terrestrial phenomena, by way of Oort cloud disturbance, was therefore considered by the authors (Napier & Clube 1979, Clube & Napier 1982, 1984, 1986). The present paper:

(i) confirms that the major terrestrial events do indeed seem to show a strong cyclicity of ~26 Myr when taken as a whole;

(ii) demonstrates that, for realistic parameters, galactic tides and low (m, v) perturbers may induce strong cyclicities of this order in the long-period comet flux; and

(iii) indicates that the periodicity requires the presence of a flat (and therefore presumably baryonic) dark matter component of density $\sim 0.15 M_{\odot} pc^{-3}$ within the disc. The total density of the local spiral arm may then be $\sim 0.3 M_{\odot} pc^{-3}$.

The great vulcanisms and mass extinctions of 65 Myr ago lie on one of these cycles: thus the dinosaur and other KT extinctions probably involved impact from a ~10 km asteroid only as one component of a prolonged bombardment episode in which multiple impacts and climatic disturbance through stratospheric dusting also played an important part (*cf.* Clube 1978, Napier & Clube 1979 with Alvarez *et al.* 1980). Support for these conclusions has come from the recent findings (Farley 1995, Farley & Patterson 1995) that extraterrestrial dust of probable cometary origin reveals both (a) the expected flux variations over the last 70 Myr, and (b) a positive correlation with the known 10^5 yr climatic cycle.

If there is continuity between the celestial hazard on geological timescales and that on historical timescales, then the climatic trauma caused by the arrival and disintegration of a giant, Earth-crossing comet is likely to be the greatest celestial hazard currently faced by mankind (Clube & Napier 1990, Bailey *et al.* 1994). The proximity of the solar system to the Galactic plane also implies, on the present hypothesis, a higher than average impact rate. Thus assessments of this latter hazard based on lunar cratering rates, (which are time-averaged over ~3.5 Gyr)

may be appreciably in error (*loc. cit.*). Likewise search programmes which are confined to the detection of current Earth–crossers may be missing the prime hazard, namely very large comets in chaotic orbits in or beyond the region of the giant planets.

A $\sim$13 Myr cycle, with weak and strong pulses interlacing, seems to be a uniquely galactic signature, and this suggests that the hypothesis may be further tested by looking for weak 'interpulses' in other terrestrial data. In fact, in some of the more recent data for which a $\sim$26 Myr cycle is claimed, such interpulses often appear to have been present during the last 100 Myr (*cf.* Grieve *et al.* 1985, Shoemaker & Wolfe 1986, Yabushita 1991; Pandey & Negi 1987). A rigorous statistical scrutiny of their significance, however, is beyond the scope of this paper.

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Figure Captions

Fig. 1. Comet flux distribution $\dot{n}(a)$, for Oort cloud concentrations γ=2.5, 0 and -2 and for ambient densities $\rho(z)$=0.2, 0.1 and 0.025 $M_\odot pc^{-3}$. Each distribution is separated by a vertical line $a = a_T$, the loss cylinder being permanently filled for $a \geq a_T$. The bulk of the cometary influx is from regions where $a \leq a_T$, for which $\dot{n}(a) \propto \rho(z)$.

Fig. 2. Simulations of the cyclic variations in comet flux due to encounters with assumed dark matter objects (density 0.15 $M_\odot\ pc^{-3}$) as the Sun oscillates vertically through the Galactic disc.
(a) In-plane perturbations. Passage at velocity $\mathbf{V}_\odot = (14, 14, 7)$ km s^{-1} in the plane, and peak amplitude 70 pc, through a field of dark stars ($M = 0.05M_\odot$) with dispersion $\sigma = (8, 8, 6)$ km s^{-1} and $Z_{1/2} = 50pc.$
(b) Out-of-plane perturbations. Passage at velocity $\mathbf{V}_\odot = (5, 5, 7)$ km s^{-1} in the plane through a uniform disc comprising a field of super-Jupiters ($M = 0.0025M_\odot$) with dispersion $\sigma = (2, 2, 2)$ km s^{-1} corresponding to the internal motions of young spiral arm material (Blaauw 1990).

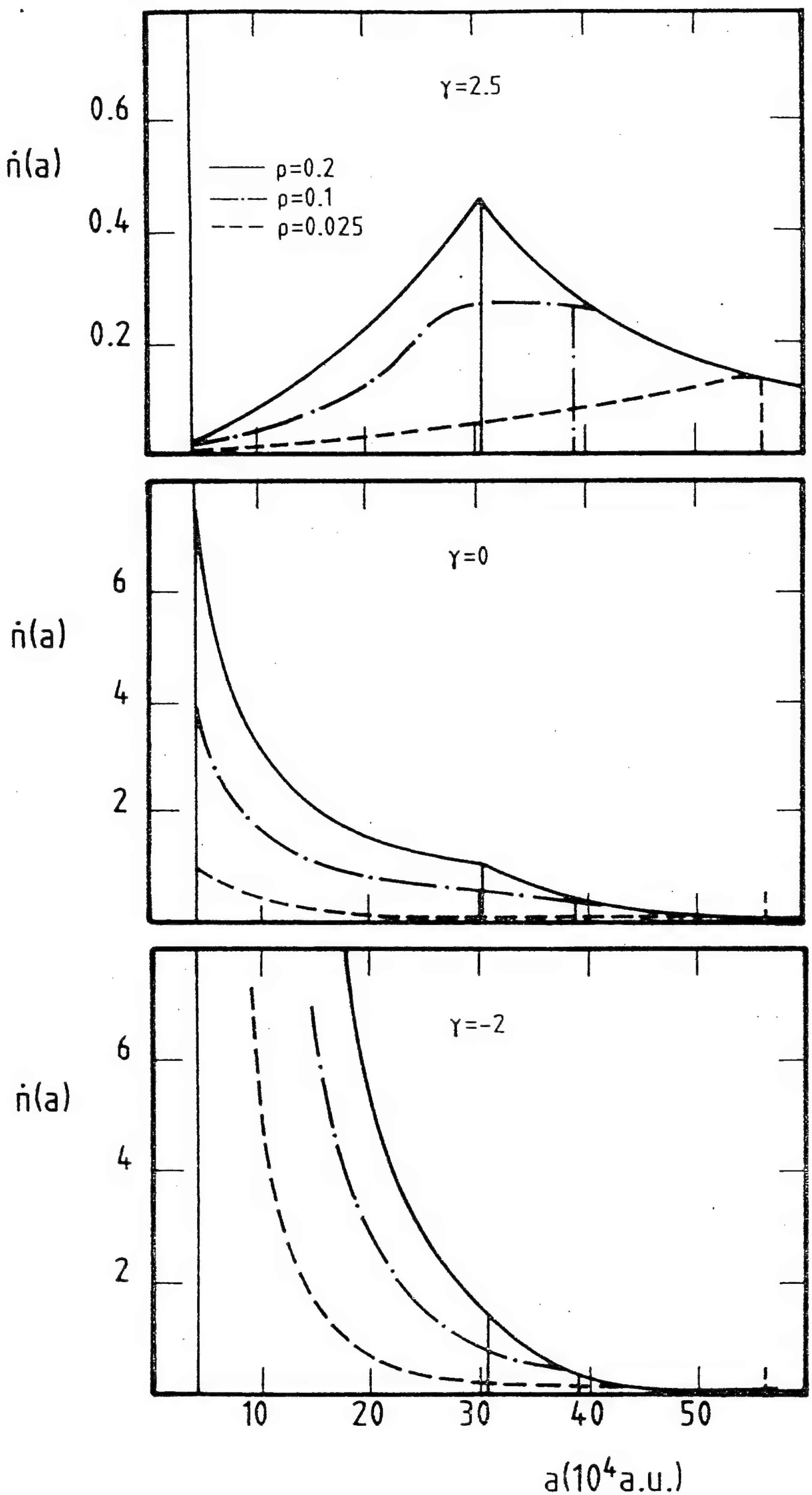
Fig. 3. The per-genera marine mass extinction record (top) after Raup & Sepkoski (1984), and (bottom) the record of global geological disturbances after Rampino & Caldeira (1992).

Fig. 4. (Left) Best-fit periodicity and phase of the Rampino/Caldeira geological data. The $(P, \phi) \sim (27 \pm 0.7, 11.1 \pm 0.7)$ Myr are stable to progressive truncation of the data. (Right) A typical run on randomized data with the same overall age distribution.

Fig. 5. The geomagnetic reversal record showing evidence of $\sim$(13,26) Myr cycles.

record	N	I	$P \pm \sigma$ Myr	$\phi \pm \sigma$ Myr	C
mass extinctions	10	14.0	25.9±0.5	12.1±1.2	0.998
geology	69	15.5	26.3±0.4	10.8±1.0	0.998
impact craters	30	6.0	27.0±0.3	11.1±0.7	0.994
field reversals	157	16.1	30.0±4.0	13.5±1.5	0.996

Table 1. Periodicities and phases found in terrestrial datasets, as discussed in the text. The errors associated with (P, ϕ), and the last decimal place in the confidence estimates C, are not precisely determined.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ρ=0.1
ρ=0.025
0.6
0.4
0.2
ṅ(a)
γ=0
6
4
2
ṅ(a)
γ=−2
6
4
2
ṅ(a)
10
20
30
40
50
a(10⁴a.u.)

Fig. 1

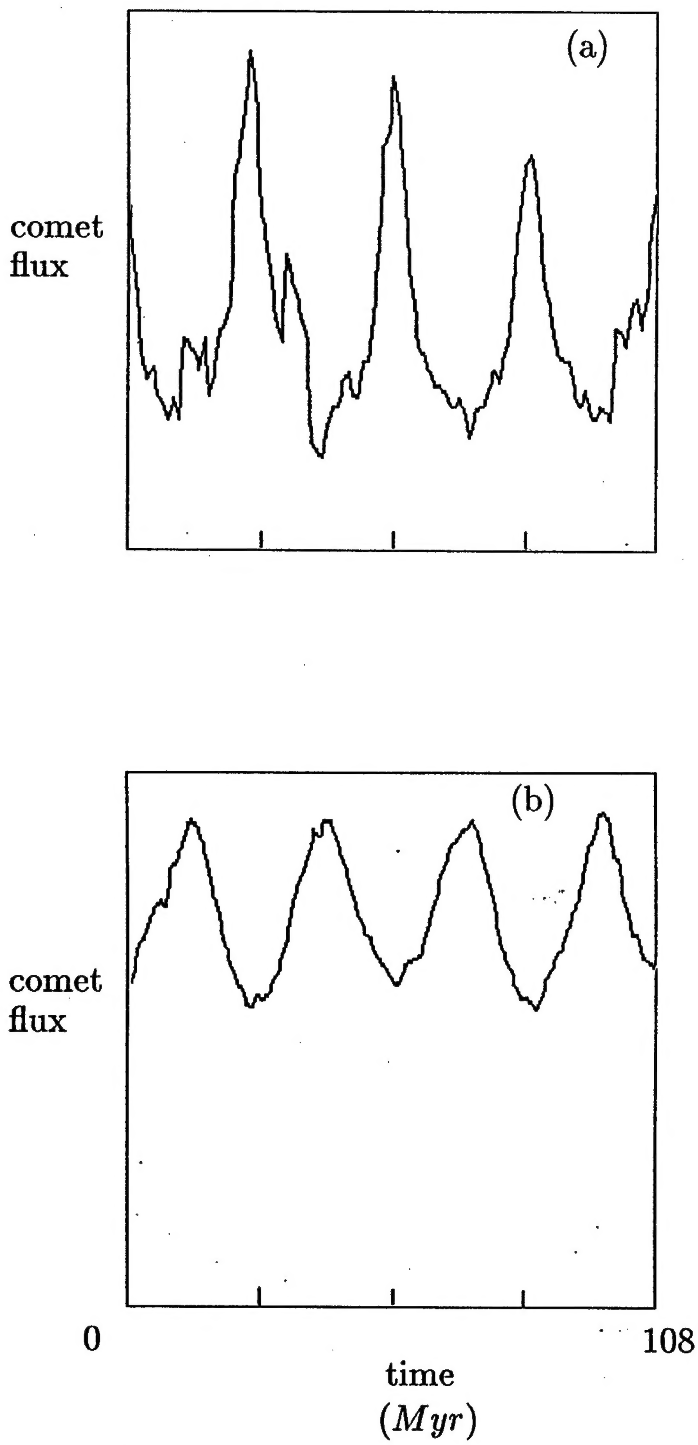


Fig. 2

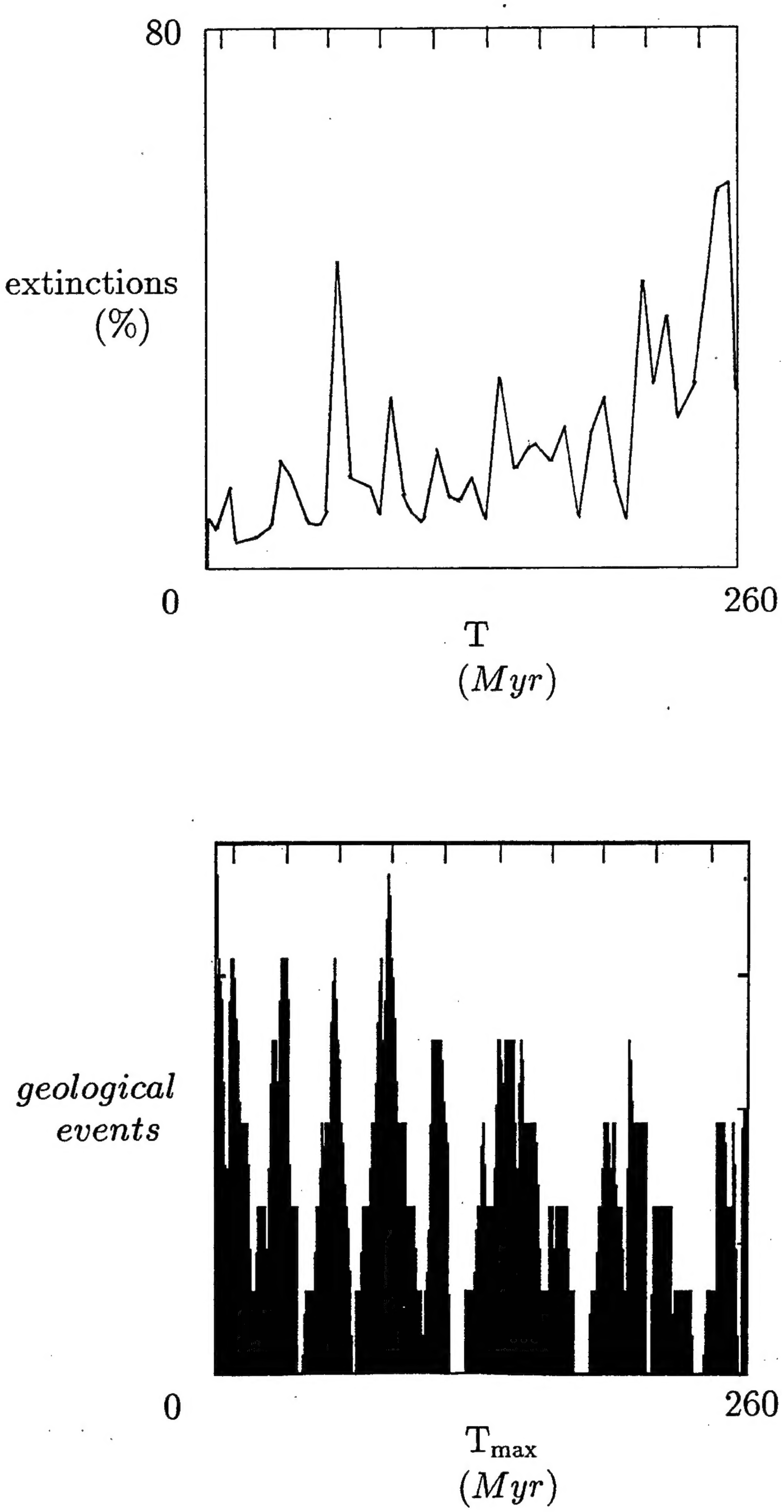
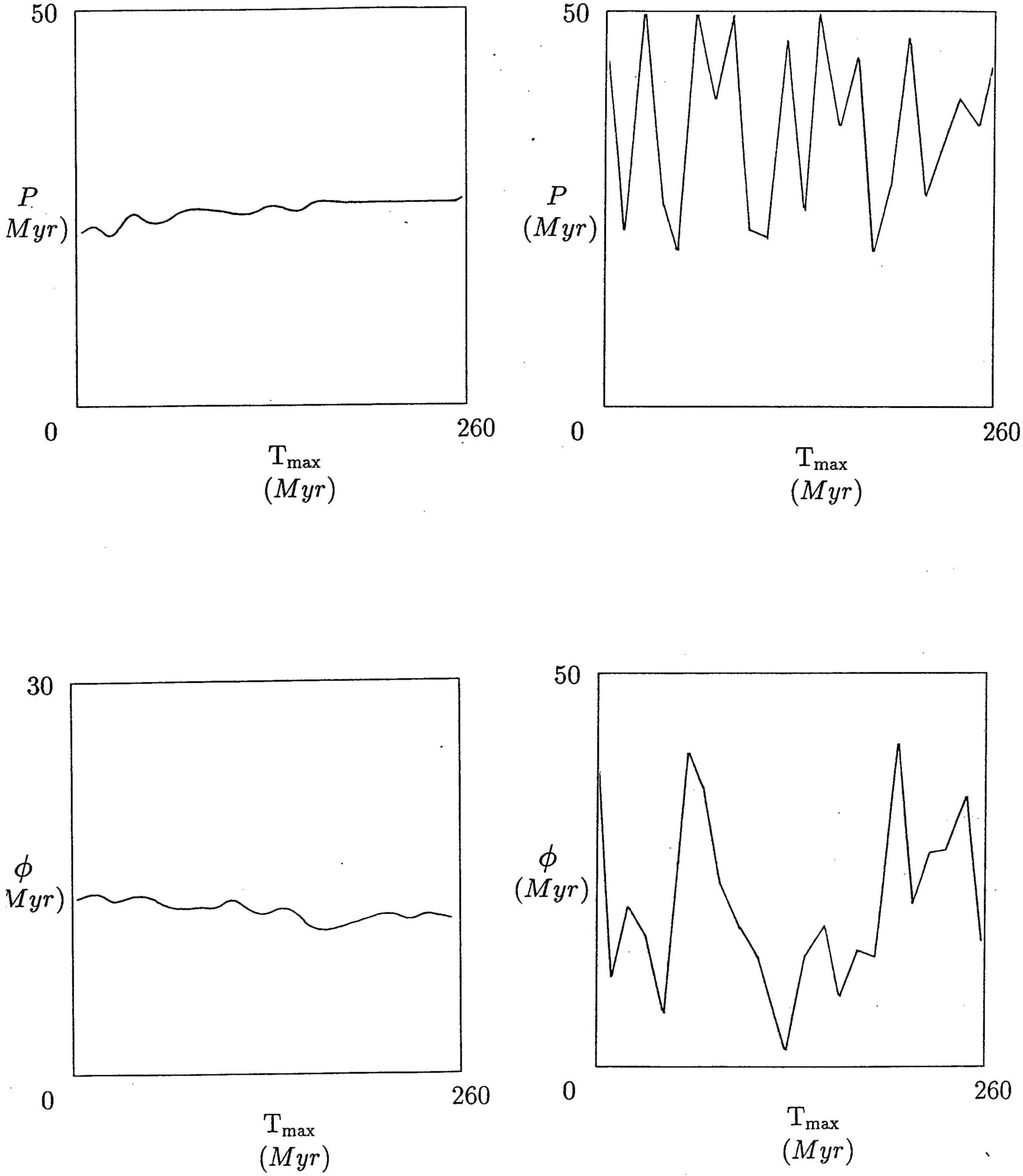


Fig. 3


50
P
Myr)
0
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P
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Tmax
(Myr)
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Myr)
0
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(Myr)
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φ
(Myr)
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Tmax
(Myr)

Fig. 4

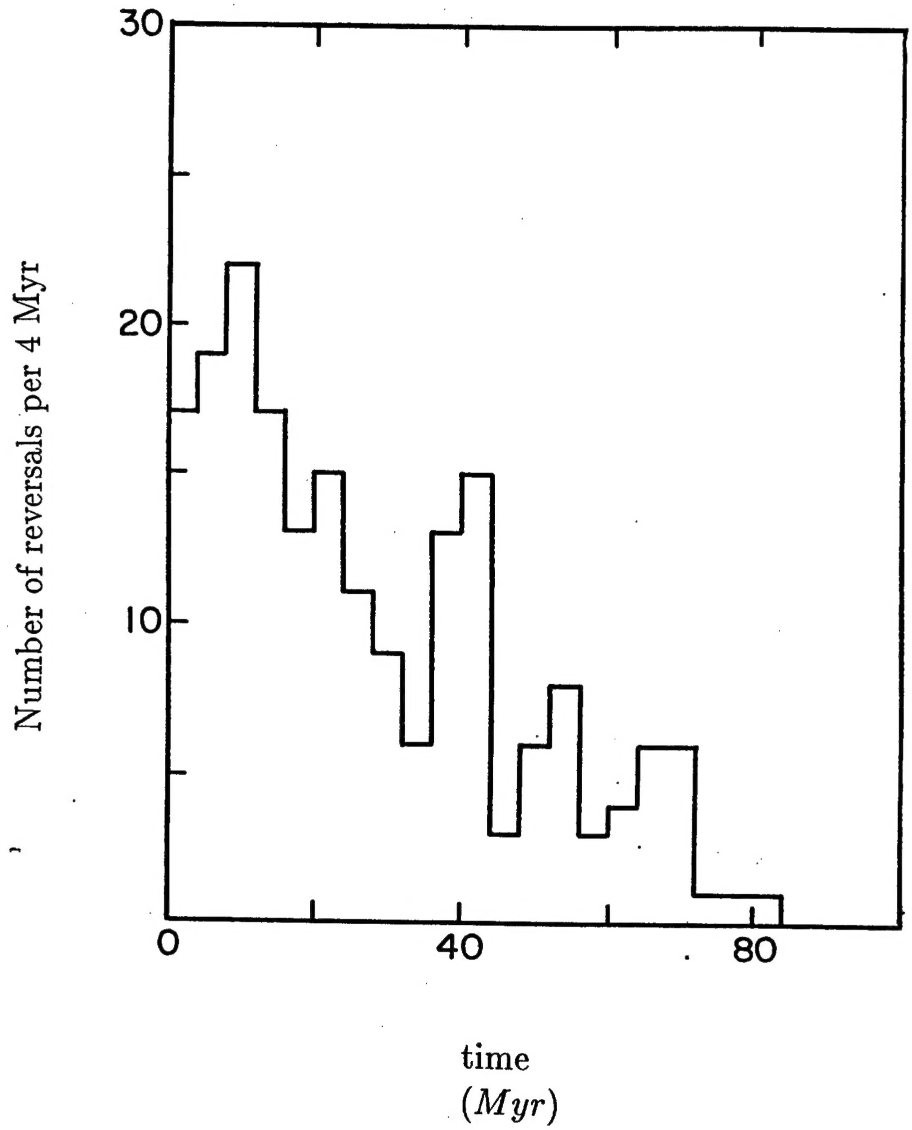

Fig. 5